Holographic lithography and two-photon lithography for the fabrication of waveguide defects in three-dimensional photonic crystals

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Citation: ICALEO **2010**, 1242 (2010); doi: 10.2351/1.5061966
View online: https://doi.org/10.2351/1.5061966
View Table of Contents: https://lia.scitation.org/toc/ica/2010/1
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HOLOGRAPHIC LITHOGRAPHY AND TWO-PHOTON LITHOGRAPHY FOR THE FABRICATION OF WAVEGUIDE DEFECTS IN THREE-DIMENSIONAL PHOTONIC CRYSTALS

Paper (N103)

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Abstract

This paper presents the conjunction of two optical lithographic techniques for the fabrication of integrated functional photonic crystal templates. Direct laser writing using a femtosecond oscilator via two-photon polymerization provided defect inscription inside a three-dimensional photonic crystal formed by holographic lighography from a single optical element. The template was fabricated in negative tone dipentaerythritol penta/hexaacrylate (DPHPA) monomers mixed with photoinitiators simplifying processing over a conventional material such as SU-8 by not requiring a pre or post bake process, but while maintaining the feature size functionality and resolution.

Introduction

Photonic crystals (PhCs) are micro-structured materials in which the dielectric constant is periodically modulated on a length scale comparable to the desired wavelength of operation [1]. In PhCs, a set of wavelengths are forbidden to propagate in the crystal, i.e. a photonic bandgap exists, similar to the electronic bandgap in semiconductors. Optical waveguides can be fabricated by adding defects to the crystal so that the light propagation with certain frequency in the photonic bandgap will be allowed along the defect [1]. It has been demonstrated that line defects in PhC can act as efficient waveguides, transmitting light around sharp corners with relatively small losses [2]. Under certain circumstances, point-like defects in PhC behave as resonant cavities and can be used as compact laser nanocavities [3] and efficient devices to couple light into PhC-based waveguides [4]. Potentially, these applications can lead to the creation of new large-scale integrated optical devices capable of all-optical signal processing [5].

In the last decade, several elegant techniques have succeeded in fabricating three-dimensional (3D) PhCs, such as conventional multilayer stacking of woodpile structures using semiconductor fabrication processes [6], colloidal self-assembly [7], multi-photon direct laser writing [8], and holographic lithography [9]. The semiconductor processing techniques provide advanced tools for building structure lay-by-layer and incorporating defects at any depth [6]. Most of the direct laser writing was based on two-photon polymerization of photosensitive resins [8]. When a high-intensity light shines on a material, the probability for two-photon absorption is proportional to the square of the optical field intensity, and thus is greatest at the center of a Gaussian laser beam. When tightly focused into the volume of a photosensitive resin, the polymerization process can be initiated by non-linear absorption of near infrared femtosecond laser pulses within the focal volume. By moving the laser focus three-dimensionally through the resin, the two-photon polymerization happens at the focus points [8]. 3D structures and defects such as missing rod in woodpile structure can be fabricated by a computer-aided sample stage control [8, 10]. The PhC structures fabricated by above two approaches are dedicated but the process is time-consuming. Fabrication of defects in self-assembled opal PhC has made headway by surface modification followed by overgrowth of opal [11] or laser direct writing of defect structures within the opal [12, 13]. However, opal PhCs were limited to face-centered-cubic structures with a relative small photonic bandgap.

Multi-beam interference-based holographic lithography has been successful for fabricating 3D PhCs by exposing a photoresist or polymerizable resin to interference patterns of laser beams [9, 14-28]. In the case of positive resist, the overexposed material is then dissolved away in the post-exposure processing. The underexposed region forms a periodic network and acts as a 3D PhC template. For negative photoresists, the underexposed regions can then be selectively removed using a developer while overexposed region becomes polymerized and forms a periodic network for PhC template. Furthermore, holographic lithography has demonstrated functionality to fabricate complex

photonic structures such as woodpile, spiral and diamond PhCs [15-17]. Multiple-beam holographic lithography was complicated when it was based on multiple bulk optical elements such as mirrors and beam splitters [9]. Recently the optical setup for holographic lithography has been simplified by using a single optical element such as flat-top prism [15] or a phase mask [18-21]. Multi-layer phase masks [22, 23] have been demonstrated for the fabrication of PhC templates by introducing a phase difference among the diffracted beams through changing the distance between two orthogonally oriented gratings. These single-beam and single-exposure processes using the multi-layer mask in holographic lithography have drastically reduced the fabrication complexity. The disadvantage is that a change in wavelength is required in order to obtain a different lattice period, which can also compromise the resist photochemistry. On the other hand, Meisel *et al.* have demonstrated that a simple cubic PhC, with a wide variety of lattice spacing, can be fabricated with a single free-space beam splitter, using three separate two-beam exposures, with no change in wavelength. To be useful for optoelectronics applications, the incorporation of engineered defects must be realized in PhC.A significant advance has been achieved on the simultaneous fabrication of functional defects in PhC templates by using a multi-beam phase-controlled one-step holographic lithography [24] and by combining the amplitude mask with the phase mask [25]. However, the process still needs to be improved to increase the functionality of the photonic crystal devices.

The strength of holographic lithography and two-photon lithography can be combined by using the holographic lithography for a rapid and flexible fabrication of 3D host PhCs and using the two-photon lithography for creating desired defects in PhCs, that in principle, can be placed in any depth with any shape. Two-photon ablation or polymerization was used to create defects in PhC template in SU-8, which were created through holographic lithography, by three research groups in 2005 [27], 2006 [28], and 2008[29]. Sun *et al.* [27] demonstrated the hybrid holographic and direct-writing method in a two-dimensionally periodic structure while Scrimgeour *et al.* described the creation of a buried waveguide structure that is commensurate with the PhC matrix. The other group [29] fabricated and developed polymer-air PhCs in SU-8 via holographic lithography and the PhCs were infiltrated with trimethylol propane triacrylate (TMPTA) and a two-photon sensitive photoinitiator for the direct writing of defects via ultrafast laser. Nice defects with a size of several lattice constants were demonstrated. These three groups used SU-8 photoresist for the holographic fabrication. The SU-8 usually requires pre-bake and post-exposure bake although it is an excellent resist for fabricating nano/mcro-structures with high aspect ratio.

In this paper, we use a different photosensitive mixture of DPHPA and photoinitiator for the hybrid holographic and two-photon lithography without pre-bake and post-exposure bake. A phase-tunable single optical element is used for the holographic fabrication of large-area woodpile-type PhC template in order to reduce the optics setup complexity. The two-photon lithography is demonstrated in the same photosensitive mixture without an infiltration of other photosensitive mixture. We create complex defect structures including letters and waveguide through direct-writing in the 3D holographically formed PhC template.

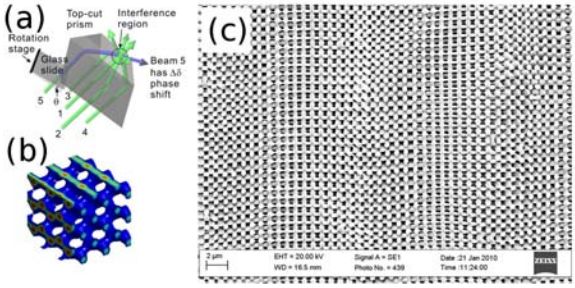

Fig. 1. (a) Schematic representation of the phase-tunable single optical element; (b) simulated interference pattern producing a woodpile structure; (c) Top view of structure developed in photoresist

Fabrication of 3D photonic structures through a prism-based holographic lithography

A 514.5nm laser beam from a Sabre Ar ion laser (Coherent Inc.) was used for the five-beam interference based holography lithography. The laser beam was circularly polarized, cleaned, expanded and collimated by spatial filter and collimating lens set. A phase-tunable single optical element (schematically represnted in Figure 1(a)) was used to construct five-beam interference pattern as described in reference 26. 3D PhCs were fabricated holographically in a negative tone photosensitive mixture mainly monomer DPHPA and photoinitiator Rose Bengal [25, 26]. The photosensitive mixture was spin-coated as a thin film on a cut glass-slide. The spin-coating speed was between 800 and 2000 rpm and the sample thickness was between 6 and 18 μm. A laser power around 250 mW was used. The exposure time was around 15 seconds. After the exposure, the photoresist was developed in propylene glycol methyl ether acetate for several hours and then washed by iso-propanol for 20

seconds and left to dry in ambient air. The developed holographic sample has a surface area of 3.5x3.5 mm^2.

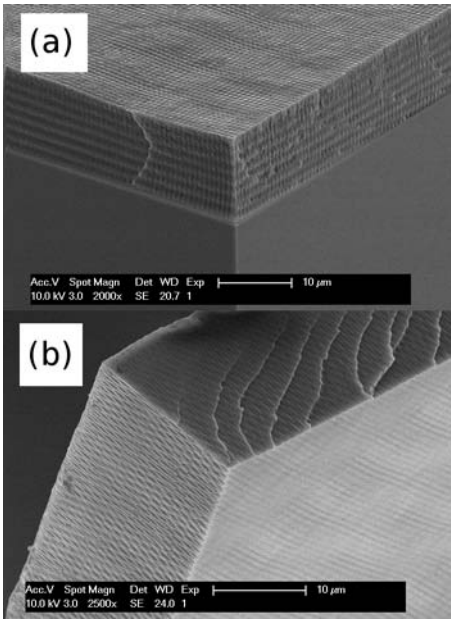

Fig. 2. (a) Oblique view of sectioned photonic crystal on glass substrate showing 3D structure; (b) close up image of cross section showing.

Figure 1(c) is of an SEM image of photonic structures developed in the photoresist, showing the quality of woodpile structure fabricated through holographic lithography. The cross-section of the fabricated sample is shown in Fig. 2(a) and an enlarged view is shown in Fig. 2(b). The expected structure is simulated in Fig. 1(b) and is determined by the wave vector k of the five beams as described by Eq. (1) and (2),

$$k_0 = K(0,\ 0,\ 1)$$

$$k_n = K\left(\sin\alpha\ \cos\frac{4n\pi}{8},\ \sin\alpha\ \sin\frac{4n\pi}{8},\ \cos\alpha\right),$$

$$\text{for n} = 1\text{-}4, \qquad (2)$$

Where α is the interference angle between the side-beam k_n and the central-beam k_0. The wave vector difference Δk can be considered as reciprocal vectors of holographically formed structures. The periodicity in x or y direction is $\lambda/\sin\alpha$ which is calculated to 0.84 μm for α=37.5°. The periodicity is measured to be 0.83 μm averaged over several SEMs. The periodicity in z-direction is $\lambda_m/(1-\cos\alpha_m)$=4.21 μm assuming the refractive index is 1.58 for the photoresist (subscript m for value inside the mixture). The measured value is 3.96 μm which is smaller than theoretic one. The difference might be due to the sample shrinkage. The wavelike long period banding in the surface of the structure in Fig. 1(c) is caused by a small sample tilt [26].

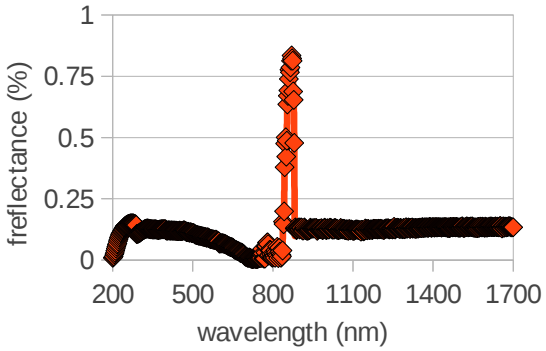

Fig. 3. The reflection spectrum from the fabricated PhC measured by ellipsometery with incident angle of 70°.

There is a strong reflection peak around 870 nm as seen in Fig. 3. A reflection peak around 940 nm due to stop-band was reported for PhC with lattice parameters of 763 nm in plane and 789 nm out of plane by Shir *et al*. [20]. For the PhC shown in Fig. 1, there are 4 layers structures in one period in z-direction. Considering that the distance between the layers is 0.99 μm and lattice parameter in plane is 0.83 μm which are similar to these values reported by Shir *et al*. [20], it is reasonable to assign the peak in Fig. 1(d) as the reflection due to the stop-band in the PhC.

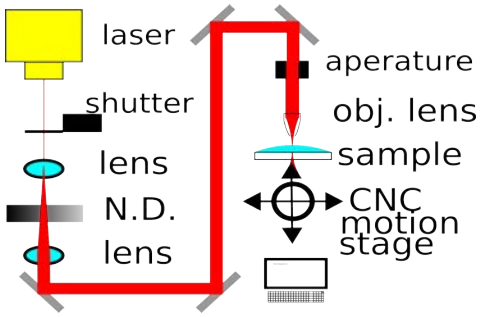

Fig. 4. Schematic of the optical setup for direct-writing using the femtosecond oscillator laser and a computer controlled motion stage.

Laser direct writing of optical waveguide through two-photon polymerization

Fig. 4 details the optical setup for direct-writing. A tunable Ti: Sapphire femtosecond laser oscillator (Chameleon, Coherent Inc.) was used with a repetition rate of 80 MHz and pulse width of 140 fs. The laser operation wavelength was 720 nm. The laser beam was

controlled through an external shutter and the laser power was attenuated through neutral density (N.D.) filters. The laser beam was expanded and then focused inside the photoresist using a 0.55 NA aspheric lens (Thorlabs). The laser power was 150 mW as measured before the aspheric lens (obj. lens). The photoresist was spin-coated on a glass slide and the slide was mounted on a three axial motion stage (Newport) which was controlled with a computer and translated with a constant speed of 2.4 mm/s. The same photoresist mixture and spin-coating on the glass slide were used as described in the above section. After the laser direct writing, the photoresist was developed in propylene glycol methyl ether acetate and then washed by iso-propanol. Fig. 2(c) shows an enlarged SEM image of the fabricated waveguide on the glass substrate. From the figure, we can see that the waveguide has clean surface and a width of 2.3 microns. It is clearly shown that the two-photon polymerization can be realized in the DPHPA mixture by the Ti: sapphire oscillator instead of an expensive ultrafast laser amplifier system.

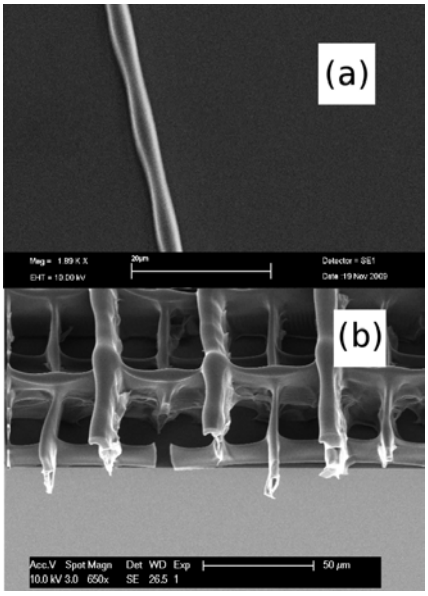

Fig. 5. (a) Single waveguide written atop glass; (b) direct written woodpile structure showing suspended features.

In order to measure the true aspect ratio, defect lines are arranged in the form of woodpile for several layers as shown in Fig. 5(b). Then we cut the woodpile and measure the size and aspect ration of defect lines for suspended part. The aspect ratio is measured to be approximately 4. It demonstrates that DPHPA can be used for constructing microstructure with high aspect ratio. On the other hand, the aspect ratio can be reduced through laser beam shaping and controlling beam scanning direction.

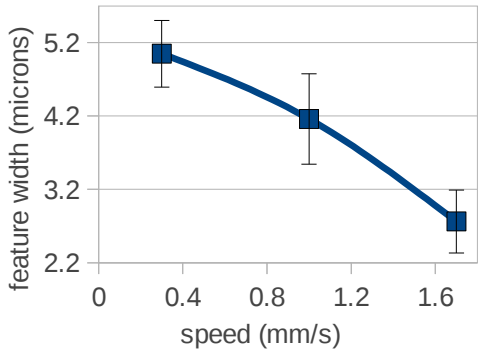

Fig. 6. (a) Oblique view of sectioned photonic crystal on glass substrate showing 3D structure; (b) close up image of cross section showing.

Fig. 6 shows the line width changes of independent waveguide structures for three scanning speeds. As the scanning speed increases, the line width decreases. These conditions are slightly perturbed when the writing inside a photonic crystal. Further detailed studies will be performed for line width as a function of laser pulse energy, wavelength and scanning speed.

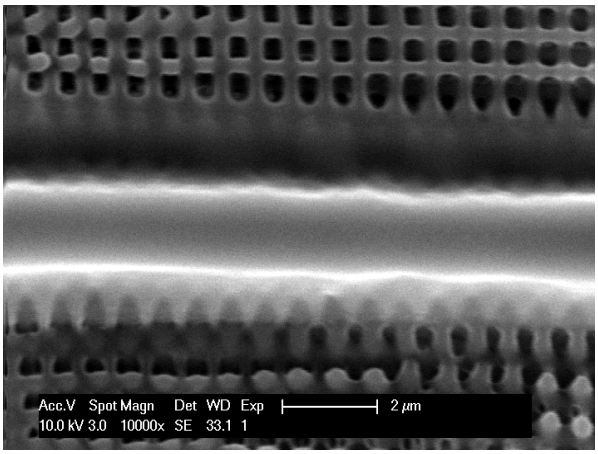

Fig. 7. Top view of half immersed waveguide in photonic crystal.

Fabrication of waveguide structures in holographic photonic crystal structures

The strength of above optical lithography techniques can be utilized for the fabrication of 3D PhCs with defects. As a demonstration, Fig. 7 shows defect structures fabricated in the 3D PhC template by combining the above two optical-lithography methods and indicated the interface quality. The spin-coated phototesist film was firstly exposed to the Ar ion laser

for the holographic lithography. After initial exposure, the glass slide is then mounted on the computer controlled motion stage. Then the femtosecond laser pulses were focused inside the previously holographically exposed resist. The motion stage was controlled such that the focal point moves across the undeveloped PhC region. The same motion speed of 2.4 mm/s was used. After exposure, the photoresist was developed in propylene glycol methyl ether acetate for six minutes and then washed with iso-propanol for 20 seconds and left to dry in ambient air. The width of the waveguide is approximately 3 microns. Although the waveguide is not in alignment with the lattice, it might be not essential because theoretic simulations have demonstrated an existence of guide mode for zig-zag defects in PhC [30].

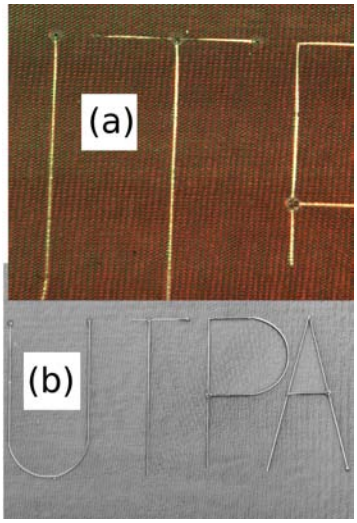

Fig. 8. (a) Optical microscope imaged with polarizing filters showing waveguide through the photonic crystal; (b) SEM image of the same structure.

A complicated structure can also be fabricated with the two-photon lithography. Fig. 8 shows defect structures of UTPA letters fabricated in the 3D PhC template, which clearly demonstrates the capability of direct laser of complex structure through the two-photon lithography in holographic structure. The fabrication of completely buried waveguide in PhC has been performed. Further characterization can be done through optical fiber butt coupling and ccd imaging or by adding fluorescent dye into the photosensitive mixture for imaging [28, 31].

Summary

In summary, this paper demonstrated the capability of optical fabrications of PhCs with defect structures in DPHPA instead of SU-8 through a simplified lithographic process without pre-bake and post-exposure bake. The flat-top four-side prism-based holographic lithography was used for the rapid fabrication of large area 3D PhC templates with woodpile-type structure. Two-photon lithography was capable to write complex defect structures in the holographically formed 3D PhCs in DPHPA with a clear interfacial connection. Thus DPHPA can used for holographic lithography, laser direct-writing, hybrid holographic and two-photon lithography and constructing nano/micro-structures with high aspect ratio.

Acknowledgements

This work is supported by research grants from the U.S. National Science Foundation under Grant Nos. DMI-0609345, CMMI-0900458, CMMI-0900564 and the US Air Force. We thank Dr. Anxiu Kuang for her SEM support.

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